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Teaching Power System Dynamics and Control Using SIMULINK

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Abstract. This paper presents an effective method used at the University of Saskatchewan for teaching power system dynamics and control. This method is based on utilizing SIMULINK in building system models and simulating their behavior. Two examples are detailed to demonstrate how the use of such a method significantly enhances the learning process. Rapid modeling of power system models and subsequent simulation results encourage the student to explore power system behavior under a variety of operating conditions, thus, significantly broadening his knowledge of power system dynamics and control.

Introduction

Small-signal (steady-state) stability and automatic load frequency control are usually major topics in a power system control graduate course. An attractive way for teaching such topics is the use of MATLAB and SIMULINK [1]. Both software packages are accessible to students in most colleges and universities. SIMULINK is an interactive environment for modeling and simulating a wide variety of dynamic systems, including linear, nonlinear, discrete-time, continuous-time and hybrid systems. It provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. The user can change model parameters on-the-fly and display results "live" during a simulation. SIMULINK is built on top of the MATLAB technical computing environment.

In this paper, the application of SIMULINK to the analysis of the steady-state stability of a single-machine infinite bus system as well as to automatic load frequency control of a two-area system is introduced. Two detailed examples for such an application are presented to demonstrate the ease and usefulness of using SIMULINK in improving students' interest, comprehension and retention.

Small-Signal Stability of a Single-Machine Infinite Bus System

In this first example, the application of SIMULINK to the analysis of a single-machine connected to a large system through a tie-line is introduced. A general system configuration is shown in Fig. 1. Analysis of systems having such a simple configuration is extremely useful in understanding basic concepts and in establishing the basis for methods of enhancing system stability through excitation control.

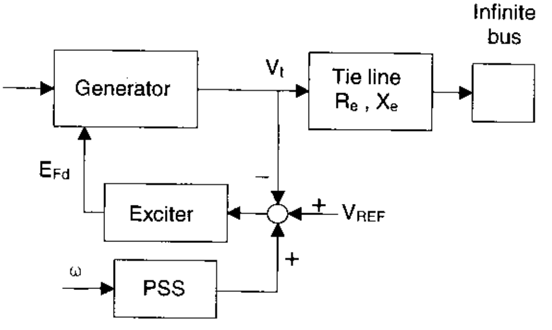

Fig. 1. A single-machine infinite bus system.

Figure 2 shows the block diagram representation of the linearized model of the power system of Fig. 1. In this representation, the dynamic characteristics of the synchronous machine are expressed in terms of the so-called K constants [2,3]. The machine excitation control system includes an automatic voltage regulator (AVR) and a speed-based power system stabilizer (PSS) [4-6]. The system parameters and operating conditions are given in the Appendix. The following are to be investigated:

1. The effect of the AVR stabilizing circuit $G_F(s)$ on the system stability.
2. The effect of the PSS on the system damping.

Figure 3 shows SIMULINK simulation model of the system of Fig. 2. In such a model, the forcing function could be a step change in either the mechanical torque or the reference voltage. The changes in the terminal voltage, field voltage, speed and the output of the PSS are displayed during simulation using scopes.

$$G_F(s)=\frac{sK_F}{1+\tau_F s},\quad G_S(s)=\frac{K_{ST}\tau_{ST}s}{1+\tau_{ST}s}\left(\frac{1+\tau_1 s}{1+\tau_2 s}\right)\left(\frac{1+\tau_3 s}{1+\tau_4 s}\right)$$

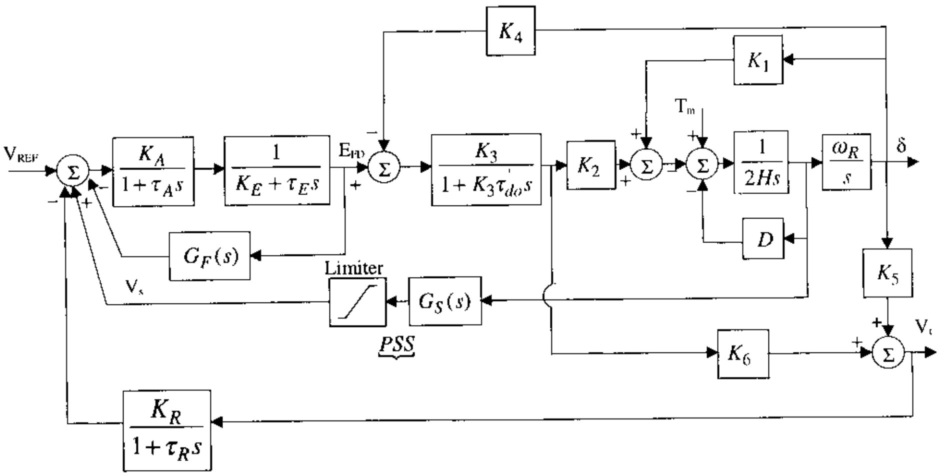

Fig. 2. **Block diagram representation of the linearized system model.**

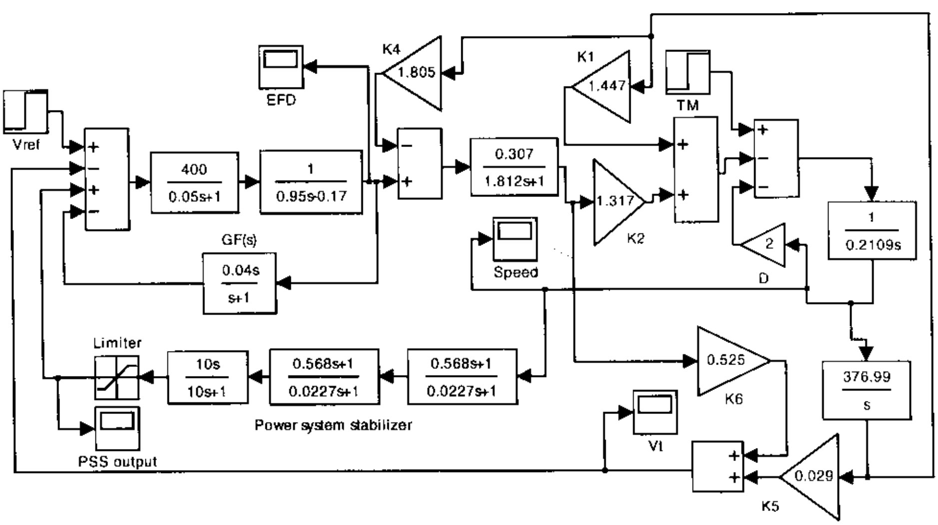

Fig. 3. **SIMULINK simulation model.**

Figure 4 illustrates SIMULINK simulation results for a step change in the reference voltage ($\Delta V_{REF} = 0.01$ p.u.) with $G_F(s) = 0$. As it can be seen, the system is unstable for such a high value of amplifier gain without the rate feedback. With $G_F(s) \neq 0$, the effect of the PSS on the system damping is demonstrated in Fig. 5 which shows a substantial improvement in damping introduced by the PSS. Figure 6 shows the effect of the rate feedback in stabilizing the system responses.

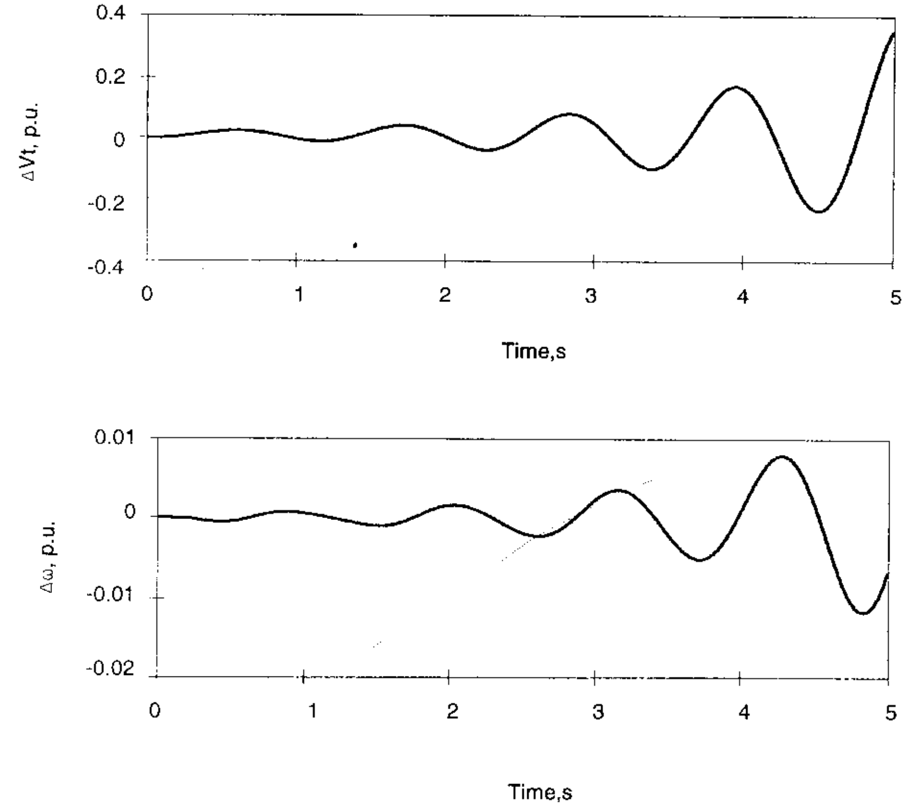

Fig. 4. Terminal voltage and speed deviations following a step increase of 0.01 p.u. in the reference voltage (without a stabilizing loop).

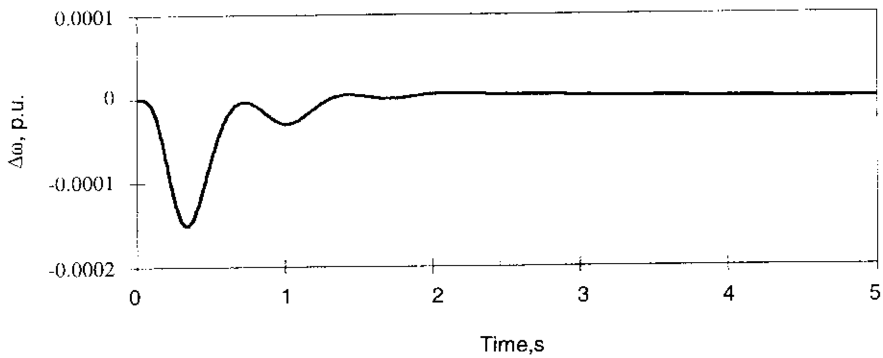

Fig. 5. Speed deviation following a step increase of 0.01 p.u. in the reference voltage (with a PSS).

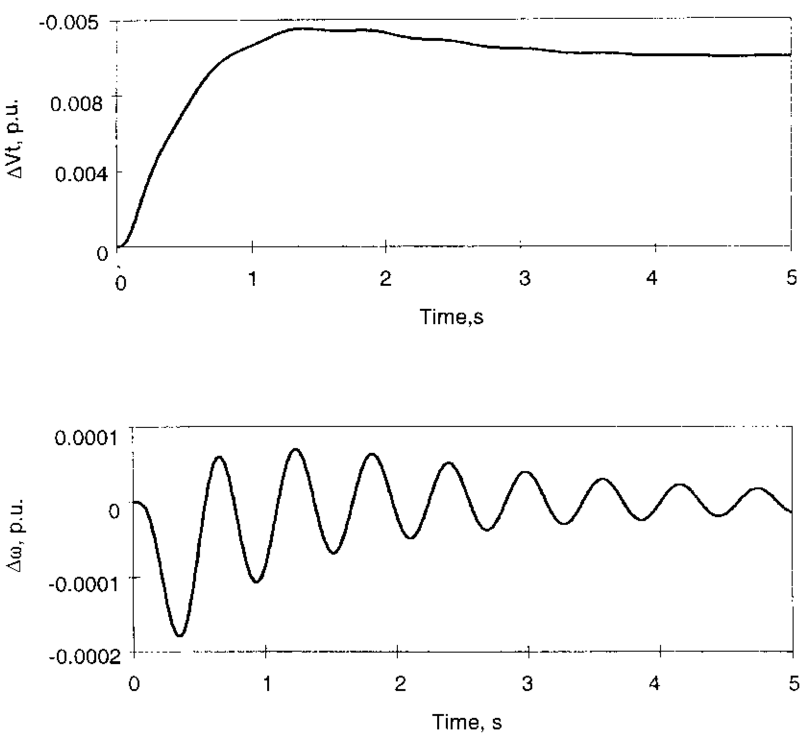

Fig. 6. Terminal voltage and speed deviations following a step increase of 0.01 p.u. in the reference voltage (with a stabilizing loop).

Automatic Load Frequency Control of Two Area System

In this second example, the application of SIMULINK to the analysis of automatic load frequency control of a two-area system is presented. Figure 7 illustrates the block diagram of a linearized model of two control areas interconnected via a tie-line [7,8]. In this model, each area is represented by an equivalent generating unit and governing system with an effective speed drop R. The tie line is represented by the synchronizing torque coefficient T*. The frequency deviations in the two areas are represented by Δf_1 and Δf_2 while the deviation in the tie-line power is represented by ΔP_{12}. A positive ΔP_{12} represents an increase in power transfer from area 1 to area 2. This in effect is equivalent to increasing the load of area 1 and decreasing the load of area 2; therefore, feedback of ΔP_{12} has a negative sign for area 1 and a positive sign for area 2. The control area errors for the two areas are:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_1 \tag{1}$$

$$ACE_2 = \Delta P_{12} + B_2 \Delta f_2 \tag{2}$$

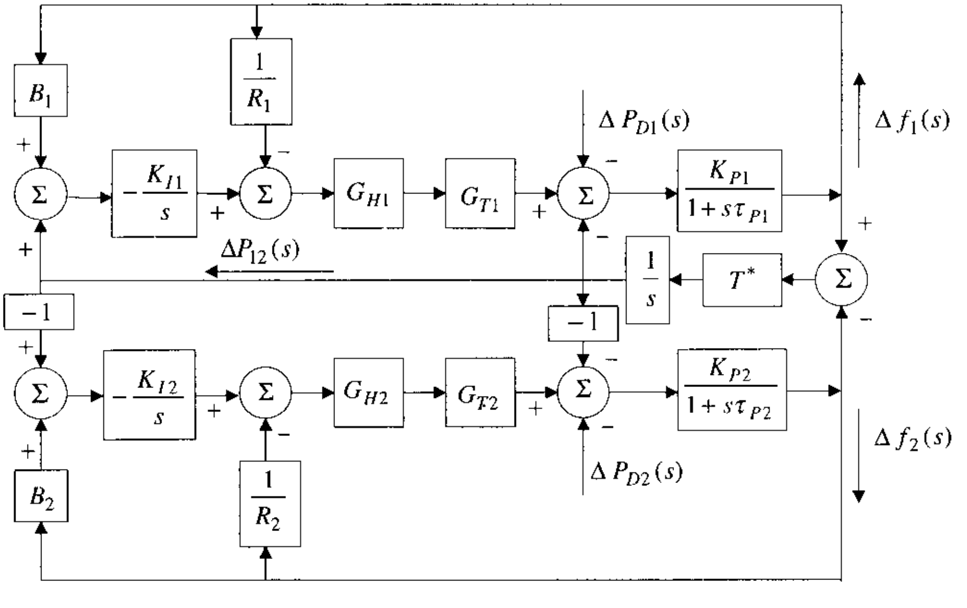

Fig. 7. Linear model of ALFC of a two-area system.

The following are to be investigated:

Case 1: Consider two equal areas, having the parameters given in the Appendix, find $\Delta f_1(t)$, $\Delta f_2(t)$ and $\Delta P_{12}(t)$ for a step change of 0.01 p.u. in the power demand of area 1 $(\Delta P_{D1} = 0.0 \text{ p.u.})$.

Case 2: Repeat Case 1 for a step change of 0.005 p.u. in the power demand of areas 1 and 2 $(\Delta P_{D1} = \Delta P_{D2} = 0.005 \text{ p.u.})$.

Figure 8 shows SIMULINK model of the two-area system of Fig. 7. In this model, the frequency deviations $\Delta f_1(t)$, $\Delta f_2(t)$ as well as the deviation in the tie-line power $\Delta P_{12}(t)$ are displayed during simulation using scopes. Figure 9 illustrates such deviations for Case 1. As it can be seen from this figure, neither the frequencies nor the tie-line power have any static error. In Case 2, where $\Delta P_{D1} = \Delta P_{D2}$, Figure 10 shows that Δf_1 and Δf_2 are identical. Notice the decrease in the frequency of oscillation in the frequency response. It should also be noted that, in this case, $\Delta P_{12}(t) = 0$.

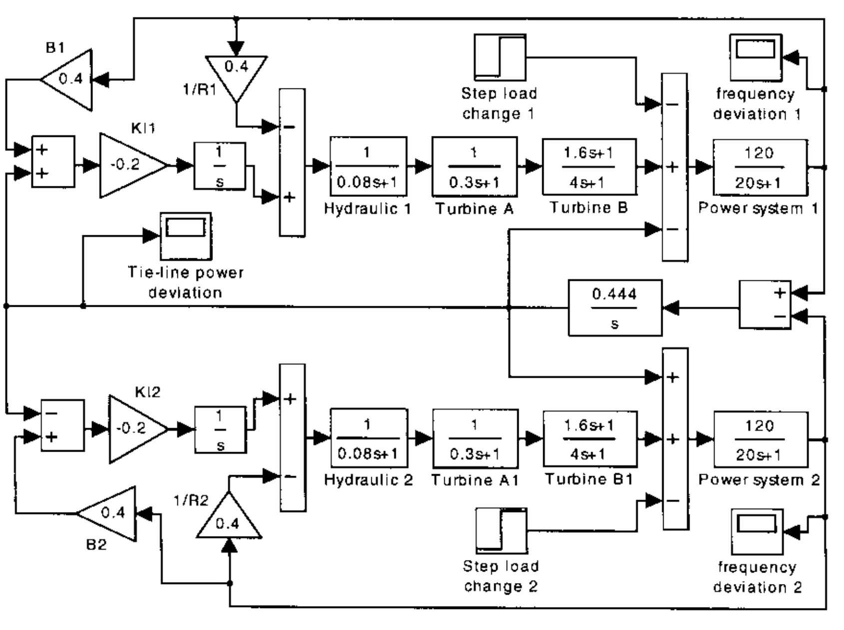

Fig. 8. SIMULINK simulation model.

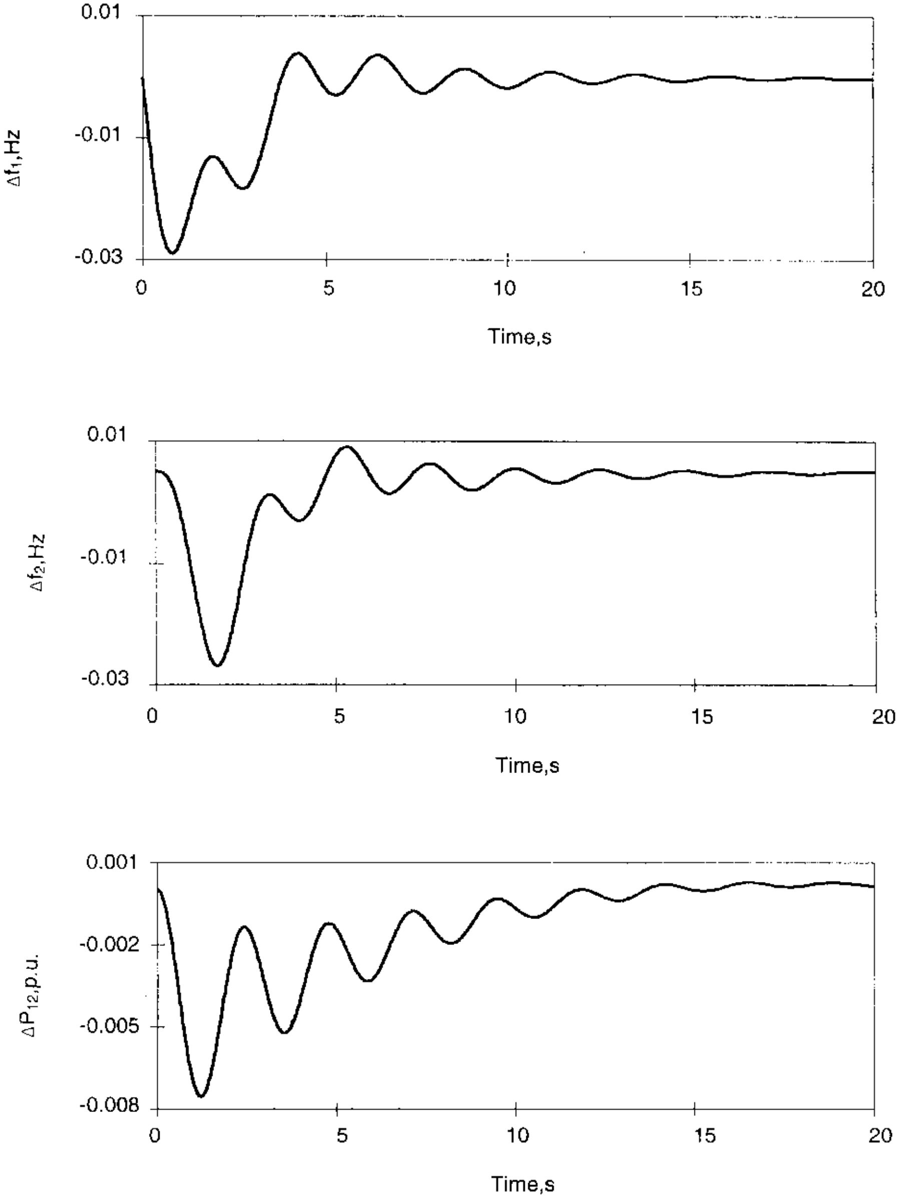

Fig. 9. Frequency and tie-line power deviations in a controlled two-area system following a step increase of 0.01 p.u. in the power demand of area 1.

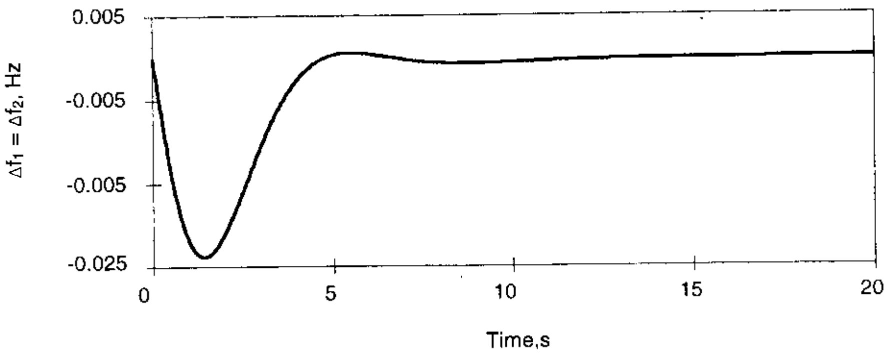

Fig. 10. Frequency deviations in a controlled two-area system following step increase of 0.005 p.u. in the power demand of each area.

Further Investigations

The students are instructed during the laboratory session to further investigate the following:

Case 3: Repeat Case 1 with $K_{I1} = K_{I2} = 2.6$ (unstable response due to the high value of the integrators gain).

Case 4: Repeat Case 1 with $B_1 = B_2 = 0$ (the system properly controls the tie-line power, but the frequency will have a static error).

Case 5: Repeat Case 1 assuming a hydraulic turbine in area 1 with a transfer function given by:

$$G_{HT1}(s) = \frac{1 - 2sT_w}{1 + sT_w}$$

$$G_H(s) = \frac{1}{1 + s\tau_H} \quad , \quad G_T(s) = \frac{1}{1 + s\tau_{CH}}\left(\frac{1 + sF_{HP}\tau_{RH}}{1 + s\tau_{RH}}\right)$$

Conclusions

In this paper, an attractive and effective approach for teaching power system dynamics and control has been presented. This approach is based primarily on using SIMULINK in building the system model and simulating its behavior. The main advantages of using such an approach are the feasibility of analyzing complex systems that cannot be treated easily analytically and that the student becomes familiar with some features of SIMULINK and the whole power of the software becomes available to him for more advanced course or project work. Moreover, the use of this type of educational methods will significantly improve the student understanding of physical system behavior which is one of the main objectives of engineering education.

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Appendix: List of Symbols and System Data

Symbol	Definition	Value
B_1	frequency bias parameter of area 1, p.u./Hz	0.4
B_2	frequency bias parameter of area 2, p.u./Hz	0.4
D	generator load damping coefficient, p.u./p.u. speed	2
E_{FD}	field voltage, p.u.	
E_q'	q-axis component of the voltage behind the transient reactance, p.u.	
F_{HP}	fraction of total turbine power generated by the HP section	0.4
$G_F(s)$	stabilizing circuit transfer function	
$G_H(s)$	hydraulic valve actuator transfer function	
$G_{HT1}(s)$	area 1 hydraulic turbine transfer function	
$G_S(s)$	power system stabilizer transfer function	
$G_T(s)$	reheat turbine transfer function	
H	inertia constant, sec	2.37
K_1	$\left.\frac{\Delta T_E}{\Delta\delta}\right\|_{E_q'}$	1.447
K_2	$\left.\frac{\Delta T_E}{\Delta E_q'}\right\|_{\delta}$	1.317
K_3	impedance factor	0.307
K_4	$\frac{1}{K_3}\frac{\Delta E_q'}{\Delta\delta}$	1.805
K_5	$\left.\frac{\Delta V_t}{\Delta\delta}\right\|_{E_q'}$	0.029
K_6	$\left.\frac{\Delta V_t}{\Delta E_q'}\right\|_{\delta}$	0.525
K_A	regulator gain	400
K_E	exciter constant related to the self-excited field	-0.17
K_F	regulator stabilizing circuit gain	0.04
K_{I1}	area 1 integral control gain, p.u. MW/Hz sec	0.2

Appendix: Contd.

Symbol	Definition	Value
K_{I2}	area 2 integral control gain, p.u. MW/Hz sec	0.2
K_{P1}	area 1 equivalent generating unit gain, Hz/p.u. MW	120
K_{P2}	area 2 equivalent generating unit gain, Hz/p.u. MW	120
K_R	regulator input filter constant	1
K_{ST}	power system stabilizer gain	1
R_1	area 1 regulation parameter, Hz/p.u. MW	2.4
R_2	area 2 regulation parameter, Hz/p.u. MW	2.4
R_E	tie-line resistance, p.u.	0.02
T_E	electric torque, p.u.	
T_M	mechanical torque, p.u.	
T^*	$2\pi\frac{\lvert V_1^o\rvert\lvert V_2^o\rvert}{X_{12}}\cos\left(\delta_1^0-\delta_2^0\right)$, synchronizing coefficient, p.u. MW/Hz sec	0.444
V	infinite bus voltage, p.u.	1.0
V_t	generator terminal voltage, p.u.	
V_{REF}	reference voltage, p.u.	
X_E	tie-line inductive reactance, p.u.	0.4
$\Delta f_1(s)$	frequency deviation of area 1, Hz	
$\Delta f_2(s)$	frequency deviation of area 2, Hz	
$\Delta P_{D1}(s)$	step change of power demand in area 1, p.u.	
$\Delta P_{D2}(s)$	step change of power demand in area 2, p.u.	
$\Delta P_{12}(s)$	change in tie-line power, p.u.	
δ	power angle, rad/sec	
s	Laplace's operator, 1/sec	
τ_1	first lead time constant, sec	0.568
τ_2	first lag time constant, sec	0.0227
τ_3	second lead time constant, sec	0.568
τ_4	second lag time constant, sec	0.0227
τ_A	regulator time constant, sec	0.05
τ_{CH}	time constant of main inlet volumes and steam chest, sec	0.3
τ'_{do}	d-axis transient open circuit time constant, sec	5.9

Appendix: Contd.

Symbol	Definition	Value
τ_E	exciter time constant, sec	0.95
τ_F	regulator stabilizing circuit time constant, sec	1.0
τ_H	hydraulic valve actuator time constant, sec	0.08
τ_{P1}	area 1 equivalent generating unit time constant, sec	20
τ_{P2}	area 2 equivalent generating unit time constant, sec	20
τ_R	regulator input filter time constant, sec	0
τ_{RH}	reheater time constant, sec	4
τ_{ST}	PSS reset time constant, sec	10
τ_w	water starting time, sec	2
ω	speed, p.u.	
ω_R	reference speed, rad/sec	376

استخدام برنامج سيميولينك في تدريس الديناميكية والتحكم في نظم القوى الكهربائية

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ملخص البحث. يقدم هذا البحث طريقة فعالة تم تجربتها في جامعة ساسكاتشوان بكندا لتدريس التحكم و الديناميكية في أنظمة القوى الكهربائية. تعتمد هذه الطريقة على استخدام برنامج المحاكاة المعروف باسم سيميولينك. و تقدم هذه الورقة مثالين بالتفصيل لشرح كيفية استخدام هذه الطريقة لتطوير العملية التعليمية وتحسينها. إن التمثيل السريع لنظم القوى الكهربائية ومن ثم محاكاة ذلك؛ يساعد ويحث الطالب لاستكشاف طريقة تصرف النظام تحت العديد من ظروف التشغيل و بهذا تتسع قدرة الطالب في فهم الديناميكية و التحكم في نظم القوى الكهربائية.